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APPLICATIONS FOR PATENT

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Title: COHERENT PROCESSING OF SATELLITE SIGNALS TO  
LOCATE A MOBILE UNIT

FIELD AND BACKGROUND OF THE INVENTION

The present invention relates to positioning systems for portable radio transceivers, and, more particularly, to a positioning system for a mobile unit of a wireless communications network, based on signals from a satellite network such as the Global Positioning System (GPS) and on signals from the base stations of the wireless communications network.

The Global Positioning System is a system of low Earth orbit satellites that transmit standard signals that can be used to establish the location of a user equipped with a suitable GPS receiver. For civilian applications, the signals are "C/A codes" that are pseudorandom noise (PN) sequences transmitted at a chip rate of 1023 KHz and a repetition period of 1023 chips, so that each frame of the PN sequence includes 1023 chips. Each satellite is assigned its own PN sequence, and the PN sequences of the various satellites are mutually orthogonal.

Superposed on the PN sequences transmitted by a GPS satellite is a Satellite Data Message, transmitted every 30 seconds at a rate of 50 bits per second. Each bit (+1 or -1) of the Satellite Data Message is modulated onto the satellite's signal by multiplying 20 consecutive frames of the PN sequence by the bit. The first 900 bits of the Satellite Data Message includes the satellite ephemeris and time model for the respective satellite. The remaining 600 bits of the Satellite Data Message include a portion of the GPS almanac, which is a 15,000 bit block of coarse ephemeris and time

model data for the entire GPS system. In addition, bits 1-8, bits 301-308, bits 601-608, bits 901-908 and bits 1201-1208 of every Satellite Data Message are identical 8-bit (160 millisecond) headers that are invariant in time and that are identical for all the GPS satellites; and bits 31-60, bits 331-360, bits 631-660, bits 931-960 and bits 1231-1260 of every Satellite Data Message are 30-bit (600 millisecond) handover words that are time-variant (these handover words include representations of the time of the week), but that, like the headers, are identical for all the GPS satellites.

Conventionally, a GPS receiver acquires and tracks the signals from at least four GPS satellites, by correlating the received signal with the satellites' respective PN sequences and locking on to the correlation peaks. Once the satellites are acquired and tracked, the GPS receiver decodes the ephemeris and time model, for each acquired satellite, from the respective Satellite Data Messages. These models include sufficient ephemeris data to enable the GPS receiver to compute the satellite's positions. The correlation peaks obtained during the continued tracking of the satellites provide measured times of arrival of these PN sequence frames. The differences between an arbitrary reference time and measured times of arrival, multiplied by the speed of light, are pseudoranges  $\rho$  from the satellites to the GPS receiver. Typically, the reference time is the time at which the satellites commenced transmission of their respective PN sequences, as measured by the GPS receiver clock, which in general is offset from the GPS system clock by an unknown time offset. A pseudorange  $\rho$  is related to the true range  $R$  of the respective satellite by  $\rho = R + c_b$ , where the range offset  $c_b$  is the time offset,  $T_0$ , of the GPS receiver relative to GPS system time, multiplied by the speed of light  $c$ :  $c_b = T_0 c$ . From these pseudoranges, and from the known positions of the satellites as functions of time, the position of the GPS

receiver is calculated by triangulation. Pseudoranges to at least four satellites are needed to solve at least four simultaneous equations of the form

$$|s-r| = \rho - c_b$$

where  $s$  is the position vector of a satellite and  $r=(x,y,z)$  is the position vector of the  
 5 GPS receiver, for the three unknown Cartesian coordinates  $x, y, z$  of the GPS receiver and for  $c_b$ . The satellites are sufficiently far from the GPS receiver that these equations can be linearized in  $x, y$  and  $z$  with no loss of accuracy.

Several methods are known for increasing the efficiency with which a GPS receiver establishes its position and for reducing the power requirements of a GPS  
 10 receiver. Schuchman et al., in U. S. Patent No. 5,365,450, which is incorporated by reference for all purposes as if fully set forth herein, teach the provision of the Satellite Data Messages to a GPS receiver integrated into a mobile unit, such as a cellular telephone, of a wireless communications network such as a cellular telephone network, by transmitting the Satellite Data Messages to the mobile unit from a base  
 15 station of the network via the control channel of the network. The Satellite Data Message is 30 seconds long, so even under ideal reception conditions with parallel processing of the signals from all the satellites in view, it necessarily takes more than 30 seconds to get a GPS position fix. Prior knowledge of the Satellite Data Message reduces this time to under 10 seconds.

20 Krasner, in U. S. Patent No. 5,663,734, which is incorporated by reference for all purposes as if fully set forth herein, teaches a GPS receiver for a mobile unit in which, as in the GPS receiver of Schuchman et al., the Satellite Data Message is obtained by a wireless link to a base station, but then, instead of processing GPS signals in real time, the GPS receiver stores up to one second's worth of signals (1000

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PN sequence frames per satellite), along with the initial time of arrival of the signals, and processes the stored signals. Groups of 5 to 10 frames each are summed and correlated with the PN sequences of satellites expected to be in view, and the resulting correlation functions are added incoherently. The summation over up to 1000 frames  
5 boosts the signal to noise ratio by a corresponding amount, and the post facto processing requires much less power than real time processing.

Duffet-Smith et al., in PCT Application WO 99/21028, which is incorporated by reference for all purposes as if fully set forth herein, teach a system and method for locating a mobile receiver ("remote unit") of a wireless communications network.

10 The remote unit and a base unit at a fixed location both receive signals on a control channel from three or more base transceiver stations (BTSs), and both correlate invariant portions of the control channel signals. Compact descriptions of the correlation peaks, such as low order polynomial fits, are transmitted to a central processor by both the base unit and the remote unit. The central processor recovers,  
15 from the correlation peaks, the time offsets of the BTS transmissions to the base and remote units. These time offsets are the functional equivalents of GPS pseudoranges. Given the (fixed) locations of the BTSs and the base unit, the central processor computes the position of the remote unit, essentially by triangulation, and transmits that location to the remote unit.

20 A GPS positioning system is predicated on the GPS receiver having a clear line of sight to at least four GPS satellites. This often is not the case in an urban environment. Urban environments commonly have cellular telephone networks installed, so in principle the system taught by Duffet-Smith et al. could be used for locating a mobile transceiver configured as a cellular telephone; but cellular

telephones generally are in simultaneous contact with at most two base stations. Sheynblatt, in U. S. Patent No. 5,999,124, Camp, in PCT Application WO99/61934, and Watters et al., in U. S. Patent No. 5,982,324, all teach methods of using signals from both GPS satellites and terrestrial BTSs to determine the location of a mobile receiver. These prior art methods generally rely on triangulation, as described above, using signals received simultaneously from a combined total of four or more GPS satellites and BTSs. As noted above, usually, at most two BTSs are "in view" simultaneously; and in a sufficiently cluttered and noisy urban environment, useable signals may be available from only one or two GPS satellites at any one time. These prior art methods also rely on all the BTSs being mutually synchronized, at least with each other if not with the GPS system. Such synchronization is optional under the GSM cellular standard. There is thus a widely recognized need for, and it would be highly advantageous to have, a system and method for locating a mobile unit of a wireless communications network, for example a mobile cellular telephone in a cluttered and noisy urban environment, that derives the location of the mobile unit from signals received sequentially from low Earth orbit satellites such as GPS satellites and from base stations of the communications network, without requiring that the BTSs be mutually synchronized.

## SUMMARY OF THE INVENTION

According to the present invention there is provided a method for determining a pseudorange, and a rate of change thereof, to a beacon that transmits a signal including a plurality of blocks, each block including a plurality of frames of a pseudonoise sequence, each block being multiplied by a bit of a data sequence, the

signal being shifted relative to a nominal frequency by a frequency shift, the method including the steps of: (a) receiving the signal; (b) digitizing the received signal, thereby producing a digitized signal including a plurality of bits; (c) arranging the digitized signal as columns of an input matrix that includes a plurality of rows, each  
5 column including consecutive the bits of the digitized signal that correspond to an integral number of frames of the pseudonoise sequence; and (d) performing a discrete orthogonal transform on each row of the input matrix, thereby producing a transformed matrix.

According to the present invention there is provided a method for determining  
10 a pseudorange, and a rate of change thereof, to each of a plurality of beacons, each beacon transmitting a respective signal including a plurality of blocks, each block including a plurality of frames of a pseudonoise sequence, each block being multiplied by a bit of a data sequence, the pseudonoise sequences and the data sequences being uniquely associated with respective satellites, all the pseudonoise sequences being of  
15 equal length, the pseudonoise sequences being mutually orthogonal, the method including the steps of: (a) receiving the transmitted signals collectively as a received signal; (b) digitizing the received signal, thereby producing a digitized signal including a plurality of bits; and (c) for each beacon, multiplying groups of the bits of the digitized signal, that correspond to the blocks of the signal transmitted by the each  
20 beacon, by respective bits of the data sequence of the each beacon.

According to the present invention there is provided a receiver for receiving a signal transmitted by a beacon, the signal including a plurality of frames of a pseudonoise sequence, including: (a) an antenna for receiving the transmitted signal; (b) a mechanism for digitizing the received signal to produce a digitized signal

including a plurality of bits; (c) a memory for storing the digitized signal as columns of a matrix that includes a plurality of rows, each column including consecutive the bits of the digitized signal that correspond to an integral number of frames of the pseudonoise sequence; and (d) a processor for performing a discrete orthogonal

5 transform on each of the rows of the matrix.

According to the present invention there is provided a locator system for locating a mobile unit, including: (a) at least one beacon having a respective pseudonoise sequence and a respective data sequence, each data sequence including a plurality of bits, each at least one beacon operative to transmit a respective transmitted

10 signal, each respective transmitted signal including a plurality of blocks, each block including a plurality of frames of the respective pseudonoise sequence, each block being multiplied by a bit of the respective data sequence, (b) a reference unit including: (i) a reference unit receiver for: (A) receiving the at least one transmitted signal as a reference unit received signal, and (B) recovering the at least one data

15 sequence from the respective reference unit received signal, and (ii) a transmitter for transmitting the at least one data sequence to the at least one mobile unit; and (c) in the mobile unit: (i) a first mobile unit receiver for receiving the at least one data sequence, and (ii) a second mobile unit receiver including: (A) an antenna for receiving the at least one transmitted signal collectively as a mobile unit received

20 signal, (B) a mechanism for digitizing the mobile unit received signal to produce a digitized signal including a plurality of bits, (C) a memory for storing, for each of the at least one beacon, an instance of the digitized signal, and (D) a processor for multiplying each of the at least one instance of the digitized signal by the bits of the respective data sequence.

According to the present invention there is provided a method for determining a location of a receiver, including the steps of: (a) providing a plurality of beacons having respective pseudonoise sequences, all the pseudonoise sequences being of equal length; (b) transmitting, by each beacon, a respective signal including a plurality of frames of the respective pseudonoise sequence; (c) receiving the transmitted signals collectively as a received signal, by the receiver; (d) inferring, for each beacon, a pseudorange and a rate of change of the pseudorange; and (e) inferring the location of the receiver from the pseudoranges and from the rates of change of the pseudoranges.

According to the present invention there is provided a method for determining a pseudorange, and a rate of change thereof, to a beacon that transmits a signal including a plurality of blocks, each block including a plurality of frames of a pseudonoise sequence, each block being multiplied by a bit of a data sequence, the signal being shifted relative to a nominal frequency by a Doppler frequency shift, the method including the steps of: (a) receiving the signal; (b) digitizing the received signal, thereby producing a digitized signal including a plurality of bits; and (c) applying a matched filter algorithm to the digitized signal to extract therefrom the pseudorange and the rate of change of the pseudorange, the matched filter algorithm including: (i) demodulating the digitized signal relative to the data sequence.

According to the present invention there is provided a method for locating a mobile unit, including the steps of: (a) providing a plurality of asynchronous stationary beacons, each stationary beacon transmitting a respective stationary beacon signal; (b) providing a plurality of mobile beacons moving on known respective trajectories, each mobile beacon transmitting a respective mobile beacon signal, all the mobile beacons being mutually synchronized; (c) for each of at least one of the



stationary beacons: (i) receiving the respective stationary beacon signal, by the mobile unit, and (ii) inferring, from the respective stationary beacon signal, at least one parameter related to a range to the each stationary beacon; (d) for each of at least one of the mobile beacons: (i) receiving the respective mobile beacon signal, by the mobile unit, and (ii) inferring, from the respective mobile beacon signal, at least one parameter related to a range to the each mobile beacon; (e) synchronizing the mobile unit and the stationary beacons to the mobile beacons by steps including: (i) providing, for each stationary beacon, a reference unit for measuring time offsets between the mobile beacons and the each stationary beacon, (ii) measuring the time offsets, by the reference units, and (iii) transmitting at least one the time offset from a respective the reference unit to the mobile unit, the inferring of the parameters being based on the synchronization; and (f) inferring, from the parameters, a location of the mobile unit.

According to the present invention there is provided a method for tracking a mobile unit, including the steps of: (a) providing a plurality of beacons, each beacon transmitting a respective ranging signal; (b) obtaining an initial estimate of a location of the mobile unit; (c) receiving, by the mobile unit, one of the ranging signals; (d) inferring, from the ranging signal, at least one parameter related to a range to the beacon that transmitted the ranging signal; and (e) obtaining an updated estimate of the location of the mobile unit, based on an initial state estimate that includes the initial estimate of the location and on an update measurement that includes the at least one parameter.

According to the present invention there is provided a locator system for locating a mobile unit, including: (a) a plurality of asynchronous stationary beacons,

each stationary beacon being operative to transmit a respective stationary beacon signal; (b) a plurality of mobile beacons, each mobile beacon operative to transmit a respective mobile beacon signal while moving on a known respective trajectory, all the mobile beacons being mutually synchronized; and (c) in the mobile unit: (i) a mobile unit clock for producing a mobile unit timing signal; (ii) a first mobile unit receiver for receiving and digitizing the stationary beacon signals; (iii) a second mobile unit receiver for receiving and digitizing the mobile beacon signals, thereby producing corresponding digitized mobile beacon signal; (iv) a memory for storing the digitized mobile beacon signal; (v) a mobile unit processor for transforming each of the stationary beacon signals into a corresponding stationary beacon pseudorange, and for transforming each of the digitized mobile beacon signals into a corresponding mobile beacon pseudorange subsequent to the storing of the each digitized mobile beacon signal in the memory; and (d) at least one reference unit including: (i) a first reference receiver for receiving the mobile beacon signals and inferring therefrom a common start time of the mobile beacon signals, (ii) a second reference unit receiver for receiving at least one of the stationary beacon signals from at least one respective the stationary beacon, (iii) a reference unit clock for producing a reference unit timing signal, (iv) a reference unit processor for inferring, for each at least one respective stationary beacon, a timing offset between a start time of the at least one respective stationary beacon signal and the common start time of the mobile beacon signals; and (iii) a transmitter for transmitting the at least one timing offset; the first mobile unit receiver being operative to receive the at least one timing offset from each at least one reference unit transmitter; the pseudoranges being with reference to both the mobile unit timing signal and the at least one timing offset.

According to the present invention there is provided a locator system for locating a mobile unit, including: (a) a plurality of beacons, each beacon transmitting a respective ranging signal; and (b) in the mobile unit: (i) a mechanism for obtaining an initial estimate of a location of the mobile unit, (ii) a receiver for receiving the ranging signals, (iii) a processor for inferring, from one of the ranging signal, at least one parameter related to a range to the beacon that transmitted the ranging signal, and (iv) an updating mechanism for updating the location estimate, based on an update measurement that includes the at least one parameter.

According to the present invention there is provided a method for tracking a mobile unit, including the steps of: (a) providing a plurality of mobile beacons, each mobile beacon transmitting a respective ranging signal; (b) providing a plurality of stationary beacons, each stationary beacon transmitting a respective ranging signal; (c) obtaining an initial estimate of a location of the mobile unit; (d) receiving, by the mobile unit, a first ranging signal from a respective beacon of one of the pluralities of beacons; (e) inferring, from the first ranging signal, at least one parameter related to a range to the beacon that transmitted the first ranging signal; (f) obtaining a first updated estimate of the location of the mobile unit, based on the initial location and on the at least one parameter that is related to the range to the beacon that transmitted the first ranging signal; (g) receiving, by the mobile unit, a second ranging signal from a respective beacon of another of the pluralities of beacons; (h) inferring, from the second ranging signal, at least one parameter related to a range to the beacon that transmitted the second ranging signal; and (i) obtaining a second updated estimate of the location of the mobile unit, based on the first updated location and on the at least

one parameter that is related to the range to the beacon that transmitted the second ranging signal.

According to the present invention there is provided a locator system for locating a mobile unit, including: (a) a plurality of mobile beacons, each mobile  
5 beacon transmitting a respective ranging signal; (b) a plurality of stationary beacons, each stationary beacon transmitting a respective ranging signal; and (c) in the mobile unit: (i) a mechanism for obtaining an initial estimate of a location of the mobile unit, (ii) a receiver for receiving the ranging signals, (iii) a processor for inferring, from each of the ranging signals, at least one parameter related to a range to the beacon that  
10 transmitted the ranging signal, and (iv) an updating mechanism for updating the initial location estimate, using the at least one parameter that is related to the range to a beacon of one of the pluralities of beacons, thereby providing a first updated estimate of the location of the mobile unit, and for updating the first updated estimate, using the at least one parameter that is related to the range to a beacon of another of the  
15 pluralities of beacons.

In the broadest sense, the present invention includes methods and systems that enable a mobile unit to determine its location by appropriate processing of signals received from mobile beacons and stationary beacons. As understood herein, a beacon is a device that includes a transmitter that transmits a signal, typically a radio  
20 frequency signal, that the mobile unit receives and then uses to determine its own location. Some of the beacons are stationary, meaning that these beacons are in fixed and known locations. Other beacons are mobile, meaning that these beacons move along known trajectories, such that at any time, the instantaneous locations of the relevant mobile beacons are known. Typically, the mobile unit is a cellular telephone,

the stationary beacons are base transceiver stations of a cellular telephone network, and the mobile beacons are satellites of a low-Earth-orbit-satellite-based positioning system such as the GPS system and the Russian GLONASS system, the trajectories of the mobile beacons then being the orbits of the satellites, as described by the satellite ephemeris and time models. More generally, however, the scope of the present invention includes any suitable beacons. For example, the stationary beacons may be special purpose beacons set up specifically to enable the tracking of a mobile unit, and the mobile beacons may be aircraft flying along known trajectories.

Although the scope of the present invention extends to the use of any suitable types of mobile and stationary beacons, the present invention is described herein in terms of the preferred and most typical mobile and stationary beacons: GPS satellites and base stations (BTSS) of a cellular telephone network. It will be clear to those skilled in the art how to adapt the principles of the present invention to other types of mobile and stationary beacons.

The mobile unit receives timing signals from the mobile and stationary beacons. In the case of the mobile beacons being GPS satellites, the timing signals are successive PN frames, modulated by the Satellite Data Messages. In the case of the stationary beacons being BTSSs, the timing signals are synchronization burst sequences transmitted in the cellular network control channel.

In order for these signals to be interpreted correctly by the mobile unit, if the cellular telephone network is asynchronous, with the BTSSs being synchronized neither to the GPS network nor to each other, then the time offsets between the individual BTSSs and the GPS system must be known by the mobile unit. Therefore, at least one reference unit is provided, for determining offsets between the BTSSs and GPS time.

One reference unit is associated with one or more BTSs. Each reference unit includes a GPS-based time reference module for receiving the PN frames from the GPS satellites and cross-correlating them with local copies of the PN sequences to determine GPS time, a cellular communications module for receiving the synchronization burst sequences from the associated BTSs, and a synchronization module for determining the timing offsets of the associated BTSs relative to GPS time. The cellular telephone network is provided with a locator service center, and the reference units transmit the timing offsets to the mobile unit via the locator service center. Optionally, one of the reference units is designated as a master reference unit that also transmits the Satellite Data Messages to the mobile unit via the locator service center. (This master reference unit may be physically integrated with the locator service center.) The mobile unit is synchronized to the cellular network in the conventional manner. This allows the mobile unit to also be synchronized approximately to the GPS network: having received the BTS timing offsets from the reference units via the locator service center, the mobile unit computes the time offset between its own clock and GPS time to within about 30 microseconds.

The mobile unit receives the satellite timing signals collectively from the GPS satellites that are in view, digitizes the combined signal, and applies matched filter algorithms to the combined signal to extract pseudoranges and rates of change of pseudoranges from the combined signal, as follows. Successive frames of the digitized combined signal are arranged as columns of a matrix. As many instances of the matrix are formed as there are satellites in view. That the mobile unit is approximately synchronized with the GPS network allows each matrix instance to be demodulated, with respect to the Satellite Data Message of the corresponding satellite,

by multiplying groups of columns of the matrix instance by corresponding bits of the Satellite Data Message of the corresponding satellites. If a master reference unit is provided, then any PN frames may be used to form the instances of the matrix; otherwise, only those PN frames, that correspond to bits of the Satellite Data

5 Messages that are common to all satellites, are used. The rows of the matrices are transformed using a discrete orthogonal transform, preferably a discrete Fourier transform. The elements of the matrices are multiplied by respective Doppler compensation factors. The columns of the matrices are convolved with the PN sequences of the in-view satellites to provide, for each in-view satellite, a signal

10 ambiguity function matrix. The squared magnitudes of the elements of these matrices include local peaks, the row and column coordinates of which correspond to candidate hypotheses for the pseudoranges to the corresponding satellites and to the rates of change of these pseudoranges. This procedure is repeated several times to provide several signal ambiguity function matrices for each in-view satellite. Then, for each

15 in-view satellite, the best hypothesis is chosen, for example, by integrating the matrices noncoherently and then identifying the most likely peak in the sum; or by passing the coordinates of all the peaks of the matrices to a "track before detect" algorithm. In either case, the peaks are identified using a constant false alarm rate detection scheme.

20 The pseudoranges to stationary beacons are simply the differences between the measured times of arrival of the synchronization burst sequences and the transmission times of the synchronization burst sequences according to the GPS system clock, multiplied by the speed of light. Note that, because the mobile unit has received the time offsets between the BTS clocks and the GPS system clock, from the reference

units via the locator service center, the mobile unit can refer these transmission times to the GPS system clock. Note also that, as a consequence, the pseudoranges to the BTSs are with reference to the same range offset,  $c_b$ , as applies to the GPS satellites. As each stationary beacon pseudorange is acquired by the mobile unit, and as each mobile beacon pseudorange - pseudorange rate pair is acquired by the mobile unit, these data are input as update measurements to a dynamic estimator to produce an updated estimate of the location of the mobile unit. Preferably, the dynamic estimator is based on a linear optimal estimator, such as a Kalman filter. The dynamic estimator requires an initial estimate of the location of the mobile unit. This initial estimate is obtained by triangulation. Alternatively, under certain conditions, the location of a predefined reference point, such as the nearest stationary beacon, may be used as the initial estimate of the mobile unit's location.

#### BRIEF DESCRIPTION OF THE DRAWINGS

The invention is herein described, by way of example only, with reference to the accompanying drawings, wherein:

FIG. 1 is a block diagram of a mobile unit of the present invention;

FIG. 2 is a schematic diagram of a locator system of the present invention;

FIG. 3 is a block diagram of a reference unit of the present invention;

FIG. 4 is a flow chart of the joint estimation of position from satellite pseudoranges, rates of change of satellite pseudoranges and base station pseudoranges.



**Abstract** The purpose of this study was to determine the effect of a 12-week training program on the physical fitness of 10-year-old children. The study was conducted in a primary school in the city of Ankara, Turkey. The study group consisted of 20 children (10 boys and 10 girls) who were randomly selected from the school. The children were divided into two groups: a control group and an experimental group. The control group did not participate in any physical education program, while the experimental group participated in a 12-week training program. The physical fitness of the children was measured at the beginning and at the end of the 12-week period. The measurements included heart rate, blood pressure, and body mass index. The results of the study showed that the experimental group had significantly higher heart rates and blood pressures at the end of the 12-week period compared to the control group. Additionally, the experimental group had a significantly lower body mass index at the end of the 12-week period compared to the control group. These findings suggest that a 12-week training program can improve the physical fitness of 10-year-old children.

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RF signals received from the BTSs, a memory 27 for storing the digitized BTS signals, and a cellular processor 28 for processing the digitized BTS signals with reference to timing signals from clock 22, as described below. The outputs of GPS processor 20 and cellular processor 28 are reconciled in a joint estimator 30, as described below, to produce a joint estimate of the location of the mobile unit of which mobile unit 10 is a part. GPS processor 20, cellular processor 28 and joint estimator 30 function under the overall supervision of a management unit 29. In particular, management unit 29 formulates requests for supplemental data, and, using cellular modem 26 and antenna 24, transmits these requests as RF signals to the BTSs, as described below.

Figure 2 is a schematic diagram of a locator system 40 of the present invention. Locator system 40 is based on a conventional cellular telephone network 42 that includes multiple BTSs 44, and on the GPS system, represented in Figure 2 by satellites 70. The terrestrial component of locator system 40 adds to cellular telephone network 42 a locator service center 46 and a multitude of reference units 50, at fixed and known locations. Each reference unit 50 is associated with one or more BTSs 44, and communicates with those BTSs 44 and, via the nearest of those BTSs 44, with service center 46. Mobile unit 10, using antenna 24 and cellular modem 26, also receives messages from service center 46 via the nearest BTS 44, as described below.

Figure 3 is a high level block diagram of reference unit 50. Reference unit 50 includes a cellular communications module (CCM) 52 for communicating with service center 46 via cellular network 42, a GPS-based time reference module 66, and a synchronization module 60 for synchronizing CCM 52 to GPS-based time reference

module 66 as described below. CCM 52 includes both transmission functionality 54 and reception functionality 56, via an antenna 58. GPS-based time reference module 66 receives GPS satellite signals via an antenna 68. Synchronization module 60 includes both a clock 64 for providing reference timing signals and a processor 62 for

5 establishing timing offsets between the GPS system and the BTSs 44 that are associated with reference unit 50, as described below. The main function of each reference unit 50 is to determine these timing offsets and to transmit these timing offset to locator service center 46. Optionally, one of reference units 50 is designated as a master reference unit. The master reference unit has the additional function of

10 receiving the Satellite Data Messages from satellites 70 and transmitting these Satellite Data Messages to locator service center 46.

Locator service center 46 is a node of cellular telephone network 42 whose function is to coordinate communications between mobile unit 10 and cellular telephone network 42 that relate to the self-location functionality of mobile unit 10.

15 In particular, locator service center 46, upon receipt of a query from mobile unit 10, transmits to mobile unit 10 supplemental data such as the timing offsets between the GPS system and one or more BTSs 44 and optionally the Satellite Data Messages of in-view satellites 70. Optionally, the functionality of joint estimator 30 may reside in location service center 46, with the outputs of GPS processor 20 and cellular

20 processor 28 being transmitted to location service center 46 for reconciliation.

The signal received by mobile unit 10 from the GPS system, as a function of time  $t$ , is a sum of the signals  $G(t)$  transmitted by GPS satellites 70 that are in view at time  $t$ . The signal received by mobile unit 10 from any one satellite 70, indexed by an index  $j$ , is in the form

$$G_j(t) = K_j D_j(t-\tau_j) g_j(t-\tau_j) \exp[i\omega(t-\tau_j)]$$

where  $i$  is the square root of -1;  $\tau_j$  is the true one-way propagation time of radio waves from the satellite to mobile unit **10**;  $K_j$  is an amplitude factor that depends on the true range  $R_j=c\tau_j$  to satellite  $j$  at time  $t$ , and on the GPS antenna gain pattern;  $D_j(t-\tau_j)$  is the Satellite Data Message of satellite  $j$  at time  $t-\tau_j$ ;  $g_j(t-\tau_j)$  is the PN sequence of satellite  $j$  at time  $t-\tau_j$ ; and  $\exp[i\omega(t-\tau_j)]$  is a Doppler factor whose Doppler frequency  $\omega$  depends on the radial component of the velocity of satellite  $j$  relative to mobile unit **10**, on the bias of clock **22**, and on other imperfections in mobile unit **10**. The total signal  $G(t)$  received by mobile unit **10** is the sum of these signals,  $\sum_j G_j(t)$ .

The object of the processing in GPS processor **20** is to measure  $\rho_j=R_j+c_b$  and its rate of change  $d\rho_j/dt$  for all the satellites in view. Note that all the pseudoranges  $\rho_j$  are referred to the same range offset  $c_b$ . As in the prior art methods,  $c_b$  is one of the unknowns that is solved for subsequently to determine the location of mobile unit **10**, so it is not necessary to measure  $\tau_j$  explicitly.

As in US 5,663,734, several hundred seconds worth of a digitized total GPS signal is stored in memory **18** and then processed by GPS processor **20**. One difference between US 5,663,734 and the GPS processing of the present invention is that according to the present invention, groups of many more than 5 to 10 PN sequence frames are processed coherently.

The total signal received by mobile unit **10** is oversampled by digitizer **16**, starting at an initial reception time  $t_0$ , typically at a sampling rate of between two and four samples per chip. With four samples per chip, there are a total of  $4 \times 1023 = 4092$  samples per frame. For each in-view satellite **70**, indexed by index  $j$ , these samples

are stored as successive columns of a matrix  $M_{ij}$  that, in the case of a sampling rate of four samples per chip, has 4092 rows and as many columns as the number of consecutive frames included in the computation: the first column of  $M_{ij}$ , matrix elements  $M_{ij}(1,1)$  through  $M_{ij}(4092,1)$  are the first 4092 samples, corresponding to the first millisecond's worth of data; the second column of  $M_{ij}$ , matrix elements  $M_{ij}(1,2)$  through  $M_{ij}(4092,2)$ , are the second 4092 samples, corresponding to the second millisecond's worth of data; etc., through a number of columns  $n$  equal to the number of frames of data that are stored in memory **18**, at one millisecond per frame. Preferably, between 100 milliseconds and 1000 milliseconds worth of data (100 to 1000 frames) are stored in memory **18** as matrix  $M_{ij}$  for each in-view satellite **70**.

The first processing step is to demodulate each matrix  $M_{ij}$ , *i.e.*, to remove the influence of Satellite Data Message  $D_j$ . This is done by multiplying groups of columns of  $M_{ij}$  by the corresponding bits of  $D_j(t-\tau_j)$ . A necessary prerequisite for this demodulation is for the bits of  $D_j$  to be aligned with the columns of  $M_{ij}$  to within about one millisecond. This alignment is referred to herein as "approximate synchronization" of mobile unit **10** with the GPS system.

Cellular telephone network **42** may be synchronized to the GPS system clock in any case, for example, if cellular telephone network operates according to the CDMA IS-95 standard. Mobile unit **10** is synchronized to cellular telephone network **42** in the conventional manner. Because cellular telephone network **42** is time-aligned (synchronized) with GPS system time, mobile unit **10** also is synchronized to GPS system time and therefore is able to demodulate matrix  $M_{ij}$  relative to Satellite Data Message  $D_j$ .

If cellular telephone network **42** is not synchronized to the GPS system clock, and, in particular, if BTSs **44** are not synchronized to each other, mobile unit **10** nevertheless can obtain, from reference units **50** via locator service center **46**, the transmission times of the synchronization burst sequences of BTSs **44** according to the GPS clock. When CCM **52** of a reference unit **50** receives a synchronization burst sequence from one of the BTSs **44** associated with reference unit **50**, synchronization module **60** determines the time offset between that BTS **44** and the GPS system with reference to clock **64**. Because the locations of reference unit **50** and the associated BTSs **44** are fixed and known, the propagation time from each associated BTS **44** to reference unit **50** also is known, so the time offset is referred to the time at which that BTS **44** transmitted the synchronization burst sequence, and not the time at which reference unit **50** received the synchronization burst sequence. CCM **52** then transmits this time offset to locator service center **46**. This is done for the synchronization burst sequence of each associated BTS **44**, so that locator service center **46** always has a current list of time offsets of all BTSs **44** from the GPS system. Finally, mobile unit **10** receives the current time offsets of the relevant BTSs **44** from locator service center **46** on request. The time offset of the nearest BTS **44** from the GPS system is used by mobile unit **10** to correct the nominal transmission times of the synchronization burst sequences from the nearest BTS **44** for this offset, and so to obtain an estimate of its own time offset  $T_0$  from GPS system time to within 30 microseconds. The time offsets of BTSs **44** from the GPS system also are used to obtain BTS pseudoranges that are referred to range offset  $c_b$ , as described below.

If the frames that are used to construct matrix  $M_{ij}$  correspond to Satellite Data Message header bits or to Satellite Data Message handover word bits, which are

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for the  $(r,d)$  element of matrix  $\mathbf{M}_{llj}$  is  $\exp\left(-\frac{2\pi ir}{m}\left(\frac{d}{n}+h\right)\right)$ , where  $m$  is the number of

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1999 1998 1997 1996 1995 1994 1993 1992 1991 1990 1989 1988 1987 1986 1985 1984 1983 1982 1981 1980 1979 1978 1977 1976 1975 1974 1973 1972 1971 1970 1969 1968 1967 1966 1965 1964 1963 1962 1961 1960 1959 1958 1957 1956 1955 1954 1953 1952 1951 1950 1949 1948 1947 1946 1945 1944 1943 1942 1941 1940 1939 1938 1937 1936 1935 1934 1933 1932 1931 1930 1929 1928 1927 1926 1925 1924 1923 1922 1921 1920 1919 1918 1917 1916 1915 1914 1913 1912 1911 1910 1909 1908 1907 1906 1905 1904 1903 1902 1901 1900 1899 1898 1897 1896 1895 1894 1893 1892 1891 1890 1889 1888 1887 1886 1885 1884 1883 1882 1881 1880 1879 1878 1877 1876 1875 1874 1873 1872 1871 1870 1869 1868 1867 1866 1865 1864 1863 1862 1861 1860 1859 1858 1857 1856 1855 1854 1853 1852 1851 1850 1849 1848 1847 1846 1845 1844 1843 1842 1841 1840 1839 1838 1837 1836 1835 1834 1833 1832 1831 1830 1829 1828 1827 1826 1825 1824 1823 1822 1821 1820 1819 1818 1817 1816 1815 1814 1813 1812 1811 1810 1809 1808 1807 1806 1805 1804 1803 1802 1801 1800 1799 1798 1797 1796 1795 1794 1793 1792 1791 1790 1789 1788 1787 1786 1785 1784 1783 1782 1781 1780 1779 1778 1777 1776 1775 1774 1773 1772 1771 1770 1769 1768 1767 1766 1765 1764 1763 1762 1761 1760 1759 1758 1757 1756 1755 1754 1753 1752 1751 1750 1749 1748 1747 1746 1745 1744 1743 1742 1741 1740 1739 1738 1737 1736 1735 1734 1733 1732 1731 1730 1729 1728 1727 1726 1725 1724 1723 1722 1721 1720 1719 1718 1717 1716 1715 1714 1713 1712 1711 1710 1709 1708 1707 1706 1705 1704 1703 1702 1701 1700 1699 1698 1697 1696 1695 1694 1693 1692 1691 1690 1689 1688 1687 1686 1685 1684 1683 1682 1681 1680 1679 1678 1677 1676 1675 1674 1673 1672 1671 1670 1669 1668 1667 1666 1665 1664 1663 1662 1661 1660 1659 1658 1657 1656 1655 1654 1653 1652 1651 1650 1649 1648 1647 1646 1645 1644 1643 1642 1641 1640 1639 1638 1637 1636 1635 1634 1633 1632 1631 1630 1629 1628 1627 1626 1625 1624 1623 1622 1621 1620 1619 1618 1617 1616 1615 1614 1613 1612 1611 1610 1609 1608 1607 1606 1605 1604 1603 1602 1601 1600 1599 1598 1597 1596 1595 1594 1593 1592 1591 1590 1589 1588 1587 1586 1585 1584 1583 1582 1581 1580 1579 1578 1577 1576 1575 1574 1573 1572 1571 1570 1569 1568 1567 1566 1565 1564 1563 1562 1561 1560 1559 1558 1557 1556 1555 1554 1553 1552 1551 1550 1549 1548 1547 1546 1545 1544 1543 1542 1541 1540 1539 1538 1537 1536 1535 1534 1533 1532 1531 1530 1529 1528 1527 1526 1525 1524 1523 1522 1521 1520 1519 1518 1517 1516 1515 1514 1513 1512 1511 1510 1509 1508 1507 1506 1505 1504 1503 1502 1501 1500 1499 1498 1497 1496 1495 1494 1493 1492 1491 1490 1489 1488 1487 1486 1485 1484 1483 1482 1481 1480 1479 1478 1477 1476 1475 1474 1473 1472 1471 1470 1469 1468 1467 1466 1465 1464 1463 1462 1461 1460 1459 1458 1457 1456 1455 1454 1453 1452 1451 1450 1449 1448 1447 1446 1445 1444 1443 1442 1441 1440 1439 1438 1437 1436 1435 1434 1433 1432 1431 1430 1429 1428 1427 1426 1425 1424 1423 1422 1421 1420 1419 1418 1417 1416 1415 1414 1413 1412 1411 1410 1409 1408 1407 1406 1405 1404 1403 1402 1401 1400 1399 1398 1397 1396 1395 1394 1393 1392 1391 1390 1389 1388 1387 1386 1385 1384 1383 1382 1381 1380 1379 1378 1377 1376 1375 1374 1373 1372 1371 1370 1369 1368 1367 1366 1365 1364 1363 1362 1361 1360 1359 1358 1357 1356 1355 1354 1353 1352 1351 1350 1349 1348 1347 1346 1345 1344 1343 1342 1341 1340 1339 1338 1337 1336 1335 1334 1333 1332 1331 1330 1329 1328 1327 1326 1325 1324 1323 1322 1321 1320 1319 1318 1317 1316 1315 1314 1313 1312 1311 1310 1309 1308 1307 1306 1305 1304 1303 1302 1301 1300 1299 1298 1297 1296 1295 1294 1293 1292 1291 1290 1289 1288 1287 1286 1285 1284 1283 1282 1281 1280 1279 1278 1277 1276 1275 1274 1273 1272 1271 1270 1269 1268 1267 1266 1265 1264 1263 1262 1261 1260 1259 1258 1257 1256 1255 1254 1253 1252 1251 1250 1249 1248 1247 1246 1245 1244 1243 1242 1241 1240 1239 1238 1237 1236 1235 1234 1233 1232 1231 1230 1229 1228 1227 1226 1225 1224 1223 1222 1221 1220 1219 1218 1217 1216 1215 1214 1213 1212 1211 1210 1209 1208 1207 1206 1205 1204 1203 1202 1201 1200 1199 1198 1197 1196 1195 1194 1193 1192 1191 1190 1189 1188 1187 1186 1185 1184 1183 1182 1181

Doppler compensation factors are needed, resulting in four different matrices  $M_{Iij}$  for each satellite  $j$ . Subsequently, as described below, much more accurate estimates of the Doppler frequency shifts of satellites 70 are obtained, and only one matrix  $M_{Iij}$  is needed per satellite  $j$ . For clarity, the remaining discussion of how GPS pseudoranges and pseudorange rates of change are measured according to the present invention is in terms of a single matrix  $M_{Iij}$  per satellite  $j$ .

The fourth processing step is to convolve each of the columns of each matrix  $M_{Iij}$  with the PN sequence of satellite  $j$ , to produce a matrix  $M_j$  that is equivalent to the matched filter, in range and frequency, known in the field of radar signal processing as the "signal ambiguity function". See, for example, Fred E. Nathanson, *Radar Design Principles, Second Edition* (McGraw-Hill, 1991). It is this use of demodulated signal ambiguity functions, subsequent to approximate synchronization of mobile unit 10 to the GPS system, that enables the present invention to process coherently many more than the 5 to 10 PN sequence frames that are processed coherently by Krasner in US 5,663,734. The preferred convolution method is the well-known fast convolution method, also used by Krasner in US 5,663,734: perform a discrete Fourier transform on a column of matrix  $M_{Iij}$ , multiply the transformed column by the discrete Fourier transform of the PN sequence, and invert the discrete Fourier transform of the column. Note that the multiplication of the elements of matrix  $M_{Iij}$  by the satellite-dependent parts of the Doppler compensation factors,  $\exp\left(-\frac{2\pi irh}{m}\right)$ , may be deferred to this processing step and implemented by, for each transformed column of  $M_{Iij}$ , appropriately shifting the discrete Fourier transform of the PN sequence prior to the multiplication of the transformed column by the discrete



Fourier transform of the PN sequence. Note also that the matrix elements of  $M_j$  are complex. The overall appearance of matrix  $M_j$ , in terms of the squared magnitudes of its elements, is a set of peaks above a general background level. The row coordinate of a peak is its pseudorange (units of distance) and the column coordinate (units of frequency) of a peak is proportional to the rate of change of its pseudorange (units of velocity).

Although the preferred structure of matrix  $M_{ij}$  has one frame per column, it also is possible to construct matrix  $M_{ij}$  with more than one frame per column, as long as an integral number of frames are used per column. Using one frame per column gives the optimal resolution for determining the rates of change of the pseudoranges.

A constant false alarm rate detection scheme is used to identify the peaks. Preferably, the detection scheme is based on an adaptive threshold, based on a background level that is obtained, matrix element by matrix element, by averaging the squared magnitudes of all the matrix elements in a window (for example, an 8x8 window or a 16x16 window) around the target matrix element. The set of matrix elements, whose squared magnitudes exceed their local average by a threshold factor, is in the form of isolated clusters of matrix elements, with each cluster corresponding to one peak. The coordinates of the peaks are the centroids of the clusters, weighted by the magnitudes of the matrix elements in the clusters. The threshold factor is determined by the required maximum false alarm rate, as is well-known in the art.

The output of this procedure is a set of hypotheses for the pseudorange  $\rho_j$  and its rate of change  $d\rho_j/dt$  associated with the initial reception time  $t_0$ . At this point, the hypothesis associated with the peak most likely to be the most reliable measure of  $\rho_j$  and  $d\rho_j/dt$ , for example, the highest peak, could be selected to provide the coordinates

that determine  $\rho_j$  and  $d\rho_j/dt$ . Preferably, however, several instances of the matrices  $M_j$ , based on several successive instances of the digitized total GPS signal, are generated. Preferably, between five and ten such instances of each matrix  $M_j$  are so generated. Subsequent processing is directed towards obtaining, for satellite  $j$ , values

5 of  $\rho_j$  and  $d\rho_j/dt$  that are based on all the instances of  $M_j$  processed collectively.

One method of processing the instances of  $M_j$  collectively is to integrate them noncoherently. In standard noncoherent integration, the matrix elements of all the instances are replaced by their squared magnitudes; the instances are added to each other, matrix element by matrix element, to produce a sum matrix; the false alarm

10 detection scheme described above is used to identify the peaks of the sum matrix; and the coordinates of the peak most likely to be the most reliable measure of  $\rho_j$  and  $d\rho_j/dt$ , for example, the highest peak, are taken as the values of  $\rho_j$  and  $d\rho_j/dt$ . In binary noncoherent integration, the matrix elements of all the instances are replaced by their squared magnitudes, but then the constant false alarm detection scheme is

15 used to compare each matrix element with a threshold. Matrix elements that exceed the threshold are replaced by ones, and all other matrix elements are replaced by zeros. The instances now are added to each other, matrix element by matrix element, to produce a sum matrix, and a second threshold is applied to the sum matrix to identify its peaks. Again, the coordinates of the peak, of the sum matrix, that is most

20 likely to represent the most reliable measure of  $\rho_j$  and  $d\rho_j/dt$ , are used as the values of  $\rho_j$  and  $d\rho_j/dt$ .

Another way to obtain values of  $\rho_j$  and  $d\rho_j/dt$  that are based on all the instances of  $M_j$  processed collectively is to replace the matrix elements of all the instances with their squared magnitudes, as in noncoherent integration, but then to

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apply the constant false alarm rate detection scheme separately to each instance, to obtain, *for each instance*, a set of hypotheses for  $\rho_j$  and  $d\rho_j/dt$ . These hypotheses and their associated start times are input to a “track before detect” identification scheme to identify the most likely hypothesis. “Track before detect” is a method that is well known in radar technology for identifying targets in a low signal-to-noise environment. See, for example, the book by Fred E. Nathanson cited above.

The pseudoranges to BTSs 44 are the differences between the measured times of arrival of the synchronization burst sequences and the nominal transmission times of the synchronization burst sequences according to the GPS system clock. If cellular telephone network 42 is synchronized to the GPS system clock, then the nominal transmission times of the synchronization burst sequences, according to clock 22, are offset from their true times by the same time offset,  $T_0$ , as the time offset by which the nominal transmission times of the PN sequences by satellites 70, according to clock 22, are offset from *their* true times. As a result, all the pseudoranges, both to satellites 70 and to BTSs 44, share the same range offset  $c_b$ . If cellular telephone network 42 is not synchronized to the GPS system clock, then mobile unit 10 obtains the time offsets of BTSs 44 from the GPS system from locator service center 46, as described above in the context of the approximate synchronization of mobile unit 10 with the GPS system for the purpose of demodulation. Mobile unit 10 then uses these time offsets to correct the times of arrival of the synchronization burst sequences from BTSs 44, as measured by clock 22, so that the pseudoranges to BTSs 44 are referred to the same range offset  $c_b$  as the pseudoranges to satellites 70. The pseudoranges to the in-view satellites 70, the rates of change of the pseudoranges to the in-view satellites 70, and the pseudoranges to BTSs 44 are input to joint estimator 30.

The method used by joint estimator 30 to combine pseudoranges  $\rho$  and pseudorange rates of change  $d\rho/dt$  from GPS processor 20, and estimated pseudoranges  $\rho$  from cellular processor 28 to derive the location of mobile unit 10 now will be discussed. The essence of this method is to use each new measurement (a pseudorange  $\rho$  and pseudorange rate of change  $d\rho/dt$  relative to a particular satellite 70 or a pseudorange  $\rho$  relative to a particular BTS 44), as that measurement is obtained, to update an *a priori* estimate of the location vector  $\mathbf{r}=(x,y,z)^T$  and of the velocity vector  $\mathbf{v}=(v_x,v_y,v_z)^T$  of mobile unit 10. (It is for this reason that this measurement is referred to herein as an “update measurement”.) If mobile unit 10 were to remain stationary between successive measurements and if range offset  $c_b$  were to remain constant between successive measurements, or if four or more measurements were to be obtained from matrices  $\mathbf{M}_j$  computed from signals received simultaneously by mobile unit 10 from the GPS system, it would be possible to fix the location of mobile unit 10 by triangulation. Because mobile unit 10 moves and  $c_b$  may drift between successive measurements, if measurements obtained from GPS signals received by mobile unit 10 at different times are to be used, or if pseudoranges to BTSs 44 are to be used, a method of estimating  $\mathbf{r}$  that accounts for the motion of mobile unit 10 and for the drift of clock 22 must be used. Such a method is referred to herein as a “dynamic” estimation method. The preferred dynamic estimation methods belong to the class of linear optimal estimators. The most preferred dynamic estimation method is based on a Kalman filter. This method now will be described in detail.

In-between updates of  $\mathbf{r}$  and  $\mathbf{v}$ , mobile unit 10 is assumed to move in a known manner. The model of the motion of mobile unit 10 used herein as an example is



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$$Q_{k-1} = w_{k-1} w_{k-1}^T = \begin{pmatrix} RW_x & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & RW_y & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & W \end{pmatrix}$$

where  $RW_x$  and  $RW_y$  are the covariances of the process noise in the  $x$  and  $y$  directions (note that mobile unit 10 is assumed to move substantially in the  $(x,y)$  plane), modeled as random walks, and  $W$  is a range drift error covariance, modeled as white noise.

- 5 Immediately following an update of the location vector  $\mathbf{r}$  and of the velocity vector  $\mathbf{v}$  of mobile unit 10, the state vector  $\mathbf{e}$  is zero by definition. Subsequently, until the next measurement, as the navigation vector  $\mathbf{n}$  is propagated forward in time, the covariance of the state vector, an  $8 \times 8$  matrix  $\mathbf{P}$ , also is propagated forward in time:

$$\mathbf{P}_k = \mathbf{A} \mathbf{P}_{k-1}^+ \mathbf{A}^T + \mathbf{Q} \delta_k$$

- 10 Here, the superscript “+” refers to the *a posteriori* estimate of  $\mathbf{P}$  after the most recent update, and the superscript “-” refers to the *a priori* estimate of  $\mathbf{P}$ , before the next update. The initialization of  $\mathbf{P}$  is discussed below.

A measurement obtained from a signal from a satellite 70 is a two component vector,  $\mathbf{z} = (\rho, d\rho/dt)^T$ . The matrix  $\mathbf{H}_k$  that relates the state vector  $\mathbf{e}$  to this measurement

- 15 vector at time  $t_k$  is:

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$$\mathbf{H}_k = \begin{pmatrix} u_x & u_y & u_z & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & u_x & u_y & u_z & 0 & 1 \end{pmatrix}$$

where the vector  $\mathbf{u} = (u_x, u_y, u_z)$  is a unit vector from the estimated location of mobile unit 10 to satellite 70:

$$\mathbf{u} = (\mathbf{r}_k - \mathbf{s}_k) / |\mathbf{r}_k - \mathbf{s}_k|$$

$r_k$  is the *a priori* mobile unit **10** location vector, obtained by forward propagation as described above.  $s_k$  is the position vector of satellite **70** at time  $t_k$ , obtained by GPS processor **20** using the satellite ephemeris and time model of satellite **70**.

A measurement obtained from a signal from a BTS **44** is a scalar (a one-  
5 component vector),  $z=\rho$ . The matrix  $H_k$  that relates the state vector  $e$  to this measurement vector at time  $t_k$  is:

$$H_k = \begin{pmatrix} u_x & u_y & u_z & 0 & 0 & 0 & 1 & 0 \end{pmatrix}$$

where the vector  $u=(u_x, u_y, u_z)$  is a unit vector from mobile unit **10** to BTS **44**. Note that the positions of BTSs **44** are fixed and known.

10 In both cases, an estimate of  $e$  is obtained by multiplying the measurement by the Kalman gain matrix  $K_k$ :

$$K_k = P_k H_k^T (H_k P_k H_k^T + R_k)^{-1}$$

$$e = K_k z$$

where the measurement noise covariance matrix  $R_k$  is:

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$$R_k = \begin{pmatrix} \sigma_\tau^2 & 0 \\ 0 & \sigma_{d\tau/dt}^2 \end{pmatrix}$$

for a satellite measurement and

$$R_k = (\sigma_\tau^2)$$

for a BTS measurement. The diagonal elements of  $\sigma_k$  are the variances of the corresponding pseudorange and pseudorange rate of change measurement errors. A

20 new *a posteriori* estimate of  $P$  is obtained as follows:

$$P_k^+ = (I - K_k H_k) P_k$$

where  $I$  is the unit matrix. Finally, the *a posteriori* navigation vector  $\mathbf{n}_k^+$  is obtained by adding the state vector  $\mathbf{e}$  to the a priori navigation vector  $\mathbf{n}_k$ :  $x_k^+ = x_k + \delta x$ ,  $y_k^+ = y_k + \delta y$ ,  $z_k^+ = z_k + \delta z$ ,  $v_{xk}^+ = v_{xk} + \delta v_x$ ,  $v_{yk}^+ = v_{yk} + \delta v_y$ ,  $v_{zk}^+ = v_{zk} + \delta v_z$ ,  $c_{bk}^+ = c_{bk} + \delta c_b$  and  $c_{dk}^+ = c_{dk} + \delta c_d$ .

Figure 4 is a flow chart of the overall processing effected by joint estimator 30 to track the motion of mobile unit 10. The processing is initialized (block 100) with an initial estimate of the navigation vector  $\mathbf{n}$ , and by setting the diagonal elements of the covariance matrix  $\mathbf{P}$  equal to initial values that reflect the initial standard deviations of the errors in  $\mathbf{r}$ ,  $\mathbf{v}$ ,  $c_b$  and  $c_d$ . How the initial estimate of  $\mathbf{n}$  is obtained is discussed below. In block 102, joint estimator 30 determines whether a measurement vector  $\mathbf{z}$  has been obtained from GPS processor 20 or from cellular processor 28. If a measurement has not been obtained, then joint estimator 30 propagates (block 104) the navigation vector  $\mathbf{n}$  forward in time, as described above. If a measurement has been obtained, then joint estimator uses the Kalman filter described above (block 106) to obtain an *a posteriori* estimate of the navigation vector  $\mathbf{n}$ . Note that this updating of  $\mathbf{n}$  is based on a single new measurement, in contrast to the use of a Kalman filter in prior art GPS navigation, in which at least four independent simultaneous measurements are needed. This *a posteriori* estimate is reported (block 108), and joint estimator 30 again checks for a new measurement vector  $\mathbf{z}$  from GPS processor 20 or from cellular processor 28.

There are several methods by which the initial estimate of the navigation vector  $\mathbf{n}$  may be obtained. Most simply, a static estimate is used as the initial estimate of  $\mathbf{r}$  in block 100, and  $\mathbf{v}$  is initially set to zero. By “static” estimation is meant that the estimation is performed under the assumption that mobile unit 10 did not move while the measurements were made and that the range offset  $c_b$  also was stationary while the



measurements were made. The simplest "static" estimate of  $r$  is the location of a predefined reference point, such as the BTS 44 nearest to mobile unit 10.  $c_b$  and  $c_d$  also are initialized to zero. This estimate is suitable for use in block 100 of Figure 4 if the first four measurements are satellite measurements, because the error in using the location of a terrestrial reference point is much smaller than the distances to the satellites. Triangulation is used to combine initial measurements from satellites with initial measurements from BTSs 44, with the proviso that the equation used with a measurement from a BTSs 44 is the full (quadratic) triangulation equation

$$|s-r| = \rho - c_b$$

rather than the linearized equation because BTSs 44 are too close to mobile unit 10 to justify linearization of this equation. Mathematical techniques for solving simultaneous quadratic and linear equations are well-known and need not be elaborated here.

Once the tracking of mobile unit 10 has commenced, the processing described above may be made both more accurate and more efficient. For example, the Doppler frequency shifts of the signals  $G_j(t)$  may be estimated more accurately. The total Doppler frequency shift is the sum of three terms: the Doppler frequency shift due to the motion of satellite  $j$ , the Doppler frequency shift due to the motion of mobile unit 10, and a contribution from the drift of clock 22. The first term can be computed from the ephemeris and time model of satellite  $j$ . Mobile unit 10 moves sufficiently slowly that the second term is negligible. The main initial uncertainty in the total Doppler frequency shift lies in the third term; but this term may be inferred from the range drift component  $c_d$  of the navigation vector  $n$ . It then is possible to obtain an estimate of  $h$ , the integer part of the Doppler frequency shift of  $G_j(t)$ , that is much more accurate

than the initial estimate described above, for use in the Doppler compensation factors for matrix  $M_{ij}$ . Furthermore, the columns of  $M_j$  that are most likely to contain the peak corresponding to  $\rho_j$  and  $d\rho_j/dt$  can be predicted to within 10 to 20 Hz, as opposed to the 1 KHz range of the full matrix  $M_j$ , so that only these columns of matrix  $M_{ij}$  need to be produced by the discrete orthogonal transform of matrix  $M_j$ .

Alternatively, having computed a pseudorange and a rate of change thereof for one satellite 70, mobile unit estimates the clock drift term of the total Doppler frequency shift by subtracting the computed Doppler frequency shift of the nearest BTS 44 from the apparent Doppler frequency shift that corresponds to the rate of change of the pseudorange to this one satellite 70. This estimated clock drift term is added to the known Doppler frequency shifts due to the motion of the other satellites 70 to provide estimates of the total Doppler frequency shifts of the other satellites 70.

While the invention has been described with respect to a limited number of embodiments, it will be appreciated that many variations, modifications and other applications of the invention may be made.